# Decay angular distribution of $J/\psi$ measured by PHENIX

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**Abstract.** Heavy quarkonia is a powerful tool to investigate gluon dynamics in hadronic collisions. Despite the good knowledge of open heavy flavor production in pQCD calculations, non-perturbative effects in the hadronization process prevents a complete description of closed heavy flavor production mechanism from first-principles. Current models rely on empirical constraints which are still not proven to be universal. One of the most important observables is the decay angular distribution of leptons from quarkonia decays. These measurements are directly related to the density matrix elements of the production amplitude. PHENIX has started to otain these angular distributions using $p$+$p$ collisions at $\sqrt{s}$ =200 GeV/$c$ and $\sqrt{s}$ =500 GeV/$c$. These studies and the first results are reported.

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## INTRODUCTION

The density matrix elements of the production amplitude $\rho_{mm'}$ of a spin $m = \pm\frac{1}{2}$ lepton decay relative to heavy quarkonia (spin $J_z = \pm 1$) momentum direction [1, 2, 3].

$$\rho_{mm'} = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix} \tag{1}$$

Parity conservation does applies when the $\hat{z}$ coordinate lies on the production plane, hence $\rho_{-1-1} = \rho_{11}$, $\rho_{-11} = \rho_{1-1}$ and $\rho_{-10} = -\rho_{10}$. The longitudinal component of the spin is $W_L = \rho_{00}$, the transverse component is $W_T = \rho_{11} + \rho_{-1-1}$, the single spin-flip is defined as $W_\Delta = (\rho_{10} + \rho_{01})/\sqrt{2}$ and the double spin-flip is $W_{\Delta\Delta} = \rho_{1-1}$.

The angular distribution of the positive lepton is derived from these elements as

$$\begin{aligned} \frac{dN}{d\cos\vartheta\,\phi} &\propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\phi} \sin 2\vartheta \cos\phi + \lambda_\phi \sin^2\vartheta \cos 2\phi \\ \lambda_\vartheta &= \frac{W_T - W_L}{W_T + W_L} \\ \lambda_\phi &= 2W_{\Delta\Delta}/(W_T + W_L) \\ \lambda_{\vartheta\phi} &= \sqrt{2}W_\Delta/(W_T + W_L), \end{aligned} \tag{2}$$

where $\vartheta$ is the angle between the lepton and $\hat{z}$ direction and $\phi$ is the azimuthal angle.

The $\hat{z}$ direction is in the quarkonium rest frame and arbitrarily defined in the hadron-hadron collision plane. The Helicity frame (HX) uses $\hat{z}$ in the direction of the quarkonium momentum, Collins-Soper frame (CS) uses the bisector between the direction of the first colliding hadron and the opposite of the second colliding hadron as the $\hat{z}$ direction whereas the Gottfried-Jackson frame (GJ) uses one of the direction of one of the colliding hadrons. One frame can be converted to another frame by a simple rotation around the vector perpendicular to the collision plane. The angular distribution parameters $\lambda_\vartheta$, $\lambda_{\vartheta\phi}$ and $\lambda_\phi$ in the frame (B) after a plane rotation $\delta$ from the original frame (A) is [4]

$$\begin{aligned}
\lambda_\vartheta^{(B)} &= \frac{\lambda_\vartheta^{(A)} - 3\Lambda}{1+\Lambda}, \quad \lambda_\phi^{(B)} = \frac{\lambda_\phi^{(A)} + \Lambda}{1+\Lambda}, \\
\lambda_{\vartheta\phi}^{(B)} &= \frac{\lambda_{\vartheta\phi}^{(A)} \cos 2\delta - \frac{1}{2}\left(\lambda_\vartheta^{(A)} - \lambda_\phi^{(A)} \sin 2\delta\right)}{1+\Lambda}, \\
\Lambda &= \frac{1}{2}\left(\lambda_\vartheta^{(A)} - \lambda_\phi^{(A)}\right)\sin^2\delta - \frac{1}{2}\lambda_{\vartheta\phi}^{(A)} \sin 2\delta.
\end{aligned} \tag{3}$$

This transformations allow the derivation of a frame invariant spin alignment parameter

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}, \tag{4}$$

which can be used to test if a measurement made in different frames is correct.

PHENIX is one of the few collider experiments which can detect $J/\psi$ decays with no minimum $p_T$ requirement in a broad rapidity range. This allows the measurement of charmonium yields in a region where pQCD calculations have no prediction power due to infrared divergences. First $\lambda_\vartheta$ measurements of $J/\psi$ decays at mid-rapidity ($|\eta|$ <0.35) in the Helicity and Gottfried-Jackson frames are already available [5]. We are also working towards a measurement of the full azimuthal angle distribution in $\sqrt{s}$=200 GeV and $\sqrt{s}$ =500 GeV. In the following sections we present the result at mi-rapidity, discuss some technical aspects of the full angular measurement and propose another measurements making use of the polarized proton beams at RHIC.

## PHENIX ACCEPTANCE FOR THE ANGULAR DISTRIBUTION OF $J/\psi$ DILEPTON DECAYS AND EXPERIMENTAL RESULTS

PHENIX is composed by four spectrometer arms. Two central arms covers $|\eta| < 0.35$ and $\Delta\phi = \pi/2$ each. They can detect dielectron decays of $J/\psi$ over the entire $\cos(\vartheta)$ range in the HX frame, $|\cos(\vartheta)| < 0.5$ for $p_T < 1$ GeV/$c$ and full coverage for $p_T > 2$ GeV/$c$ in the GJ frame and $|\cos(\vartheta)| < 0.5$ for $p_T < 5$ GeV/$c$ in the CS frame (Figures with angular distributions in [5]). The measurement demands a detailed understanding of the trigger conditions and detector acceptance which also depends on the lepton

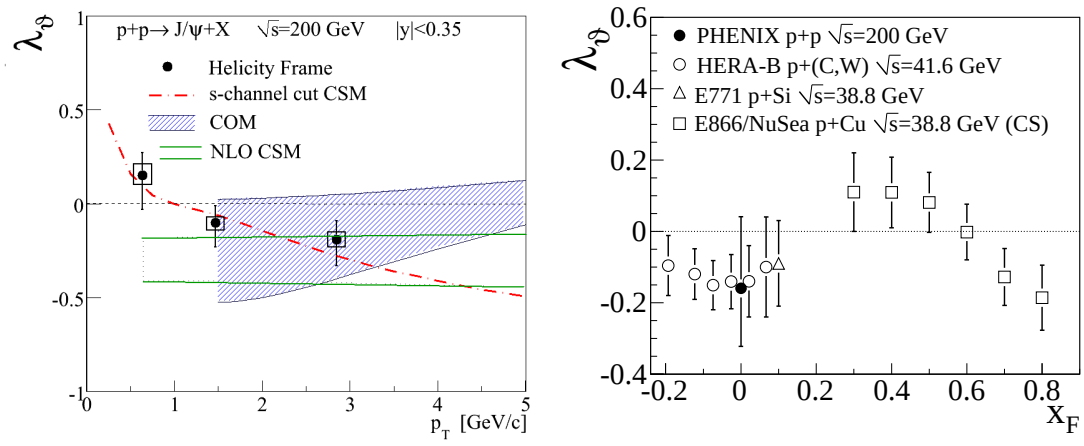


**FIGURE 1.** (Color online) (left)$J/\psi$ polarization parameter $\lambda_\vartheta$ versus transverse momentum in the Helicity frame compared with color octet (COM)[8], s-channel color singlet (CSM) [6] and NLO CSM [7]. (right) $J/\psi$ polarization parameter $\lambda_\vartheta$ versus $x_F$ in the Gottfried-Jackson and Collins-Soper from PHENIX (GJ), HERA-B (GJ) [9], E771 (GJ)[10] and E866/NuSea (CS)[11]. Plots extracted from [5].

angular distribution. In some $p_T$ ranges, the $J/\psi$ acceptance can change by up to 20% if $\lambda_\vartheta = \pm 1$. The firsts measurement of the $J/\psi$ decay angular distribution parameter at RHIC was done for $\lambda_\vartheta$ assuming $\lambda_\phi = \lambda_{\vartheta\phi} = 0$ (Figure 1). This assumption was also used in almost all measurements performed in other experiments and all current theoretical predictions.

The parameter $\lambda_\vartheta$ (commonly called polarization) is consistent with zero in HX and GJ frames given the current uncertainties. Results in lower energy fixed-target experiments using the Gottfried-Jackson frame also report a small negative polarization in agreement with PHENIX data (Figure 1-right). A trend for a dominance of the longitudinal component of the spin $(\lambda_\vartheta < 0)$ in both frames has been observed when the $J/\psi$ $p_T$ gets higher (Figure 1-left for HX frame). Theoretical predictions assuming $J/\psi$ is totally produced as color singlet states [6, 7] or assuming $J/\psi$ is mainly produced as color octet states [8] are compared to the Helicity frame result. These theoretical estimations face large uncertainties because of the unknown $\chi_c$ feed-down contribution. Current measurement at mid-rapidity has no discrimination power for these models.

Currently, PHENIX collaboration is studying all systematics involved in the acceptance of the muon decay angular distribution in the two forward arms. Each of these arms cover $1.2 < |y| < 2.2$ and $\Delta\phi = 2\pi$. The analysis are going on using the data collected in $\sqrt{s}$ =200 GeV and $\sqrt{s}$ =500 GeV $p$+$p$ runs. Figure 2 shows two examples using Helicity frame for the angular distributions obtained from detector Monte Carlo simulation assuming symmetric muons decays and what is observed in real data. The parameters $\lambda_\vartheta$, $\lambda_\phi$ and $\lambda_{\vartheta\phi}$ should be obtained from a two-dimensional fit ($\cos\vartheta$ versus $\phi$) in order to avoid correlations among the parameters. Results from these studies will allow the constraining of the density matrix (1) of inclusive $J/\psi$ production at $\sqrt{s}$ =200 GeV and $\sqrt{s}$ =500 GeV.

Future measurements also include the search of spin transfer from the polarized proton beams. The angular distribution parameters are measured in collisions with different

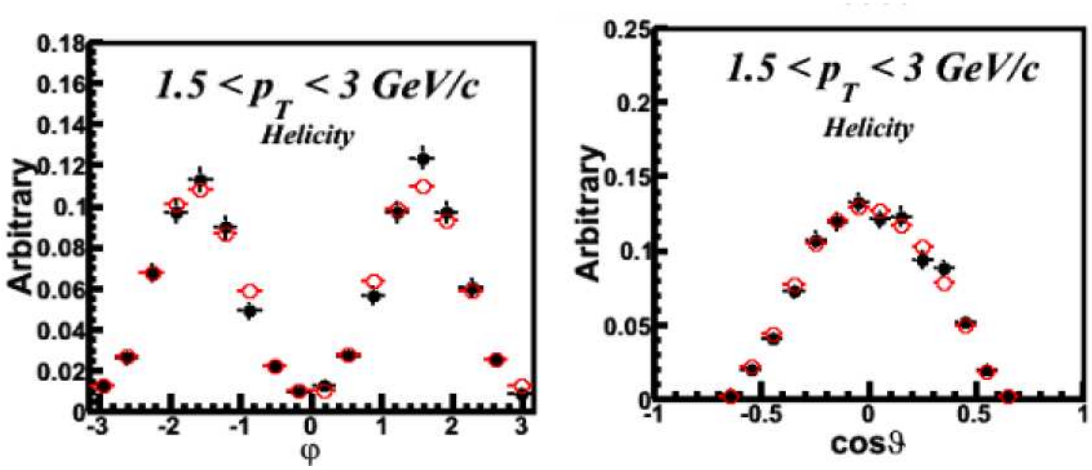


**FIGURE 2.** Example of an angular distribution in Helicity frame for muons from $J/\psi$ decays in the forward arms ($1.2< |y| <2.2$). Open symbols represents Monte Carlo detector simulation considering $\lambda_\vartheta = \lambda_\phi = 0$ and closed symbols are from real data.

proton polarizations. Gluon helicity distribution in longitudinal double spin polarization asymmetry and hints of the parton orbital momentum in transverse spin polarization asymmetry can perhaps be explored. No theoretical studies are available at this time. One of the questions is whether effects of the $c\bar{c}$ hadronization cancel out in such asymmetry observations. On the experimental point of view, uncertainties concerning detector acceptance cancel out in such measurements turning them an attractive observable.

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